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Modeling of manufacturing technologies during ramp-up

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Abstract

The production ramp-up is of increasing importance for the manufacturing industry and has a significant impact on the product's success in terms of costs and time to reach full capacity utilization (time-to-volume). During the production ramp-up the instability of the production system and the quality of manufactured products are significantly influenced by the manufacturing technologies deployed. Furthermore, an analysis of the existing approaches to optimize production ramp-ups has shown that the selection and optimization of manufacturing technologies regarding the ramp-up targets is still insufficiently considered. Therefore, the aim of this paper is the development of a new ramp-up model that enables a prediction of the ramp-up behavior of manufacturing technologies and a selection of the most suitable one according to the given ramp-up situation. Firstly, different approaches from the field of ramp-up optimization and manufacturing technology evaluation are discussed, and the deficits are pointed out. Secondly, dynamic impact factors on the ramp-up performance of manufacturing technologies are systematically identified. Thirdly, the impact factors are transferred into a new analytical model which also considers stochastic influences on the ramp-up behavior. Fourthly, the analytical model is implemented into a hybrid simulation model, which is based on a combined discrete event and continuous flow simulation. The resulting simulation model can be utilized for the calculation of ramp-up curves for different manufacturing technologies as well as for the evaluation of the ramp-up performance of the technologies investigated. Finally, the model is validated with a use case from a German automotive manufacturer.

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Keywords: Ramp-up; technology planning; manufacturing technologies; hybrid simulation

1. Introduction

Due to the shortening of product lifecycles and the increasing range of products in recent years, the production ramp-up becomes increasingly more relevant for the manufacturing industry [1–4]. Furthermore, the production ramp-up is of high importance to the economic efficiency of a new product generation [5]. A fast ramp-up leads to significant competitive advantages, whereas a ramp-up delay commonly results in a loss of image and contractual penalties [6]. Delays during the ramp-up stage are often a consequence of machine tool break-downs and insufficient process capabilities of the manufacturing technologies leading to a high quantity of defective parts [3,7]. Although manufacturing technologies and their ramp-up performance largely determine the success of the ramp-up process, they are not usually considered in ramp-up planning [6,8,9].

Therefore, the aim of the present paper is the development of a new basic model that enables a prediction of the ramp-up performance of different manufacturing technologies. In order to stress the motivation for the model development, in the state of the art approaches from the field of proactive ramp-up management are analyzed regarding the consideration of manufacturing technologies. Afterwards, the new basic model is introduced and implemented as a software prototype. Finally, the model is validated by means of a use case from a German automotive manufacturer.

Nomenclature

i	Machine tool i
j	Workpiece j
m	Module m of the machine tool i

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2. State of the art

Existing approaches from the field of technology planning are limited to the evaluation and selection of manufacturing technologies as well as to the design of technology chains without taking the ramp-up stage into account. Examples of the methodologies supporting the selection of manufacturing technologies and the design of technology chains can be found in the works of Fallböhmer, Trommer, Müller, and Stauder [10-13]. Furthermore, several scientific publications exist in the field of ramp-up management, which deal with the proactive modeling of the ramp-up of production systems [6-8,14,15]. However, none of these approaches takes into account the characteristics of the manufacturing technologies within the production systems and their impact on the success of the ramp-up stage. As of authors knowledge, only Nau addressed this topic in his dissertation [9]. However, his approach is limited to a variation of process parameters of a single manufacturing technology. Furthermore, the impact of the manufacturing technology on the output during the ramp-up stage is modeled without taking other characteristics of the technology into account, like tool wear and machine tool breakdowns [9]. Hence, there exists no generic model to predict the ramp-up curve of manufacturing technologies. Such a model is necessary to improve the accuracy of the proactive ramp-up modeling and to enable an evaluation and selection of manufacturing technologies considering not only the stage of series production.

3. Research objective and procedure

The research objective of the present paper is a new basic model to predict the ramp-up performance of manufacturing technologies. Due to the high number of influencing factors and interactions between these factors, an implementation into a software prototype is indispensable. The procedure for the model development follows the VDI 3633 standard, see Fig. 1, which provides a procedure to set up ramp-up simulations for manufacturing systems and was already successfully applied in the dissertation of Lanza for a simulation based ramp-up support [8,16].

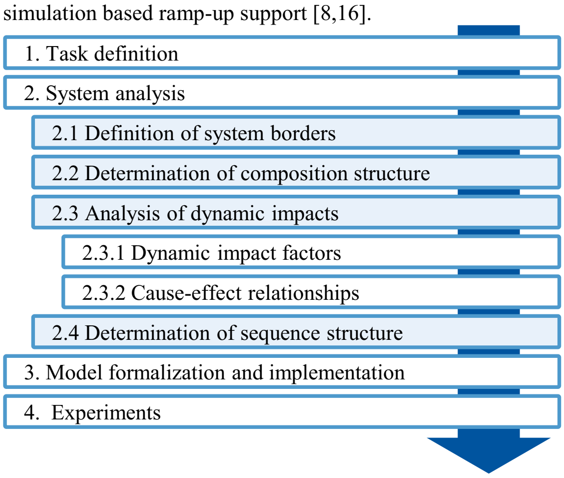

Fig. 1. Procedure for the model development [16]

Due to the strong impact of the dynamic impact factors on the manufacturing system behavior during ramp-ups, the two steps 2.3.1 and 2.3.2 were added, see Fig. 1. This enables an analysis and consideration of dynamic impact factors as well as of cause-effect relationships between them [15].

4. Ramp-up model

In the following, the new ramp-up model development according to the steps in Fig. 1 is described. Thereby, the focus of the development is on the analysis of the system "manufacturing technology" which is a subsystem of the manufacturing system.

4.1. Task definition

Firstly, the task to be carried out by the ramp-up model must be defined. This includes the definition of a target system to evaluate different manufacturing technologies or manufacturing systems. The task is the development of a basic model for a ramp-up oriented technology planning. The model is based on a proactive calculation of ramp-up curves of manufacturing technologies. For the evaluation of manufacturing technologies the target system by Klocke et al. is applied [17]. The target system considers the underlying ramp-up situation through a new procedure for a ramp-up specific weighting of the target criteria. The targets time-to-market and time-to-volume are to be directly derived as results of the ramp-up model.

4.2. System analysis – Definition of system borders

For the definition of the system borders, the relations between the elements of the super-ordinated system "manufacturing system" must be determined, see. 1. According to Westkämper and Buchholz, a manufacturing system is a unit that disposes of resources, manufacturing technologies and the corresponding machine tools as well as management functions, which are carried out by a technology planner [18,19]. Several approaches in the context of ramp-up management use the control loop analogy to describe the dynamic and instable system behavior of manufacturing systems during ramp-ups [1,8,20]. For the new ramp-up model to be developed, the control loop analogy and the basic production system model from the production theory according to Dyckhoff were applied to describe the relations between the elements of a manufacturing system [21]. Therefore, in the new ramp-up model, a manufacturing system consists of the following elements: manufacturing technology/-ies (control process), the technology planner (controller), ramp-up scenarios (actuating variable/-s), ramp-up curve/-s (feedback), disturbances from the environment (disturbance variables) and the target system (target figures), compare [21]. The manufacturing system with the subordinated system "manufacturing technology/-ies" is depicted in Fig. 2. In the upper part of Fig. 2 the technology planner is responsible for the selection of manufacturing technology/-ies and corresponding process parameters. Based on this, ramp-up scenarios (actuating variables) are created, which are simulated with the ramp-up model for manufacturing technologies that also considers disturbances from the environment. The output of the model developed in this paper are different ramp-up curves which are evaluated based on the case specific target system [17]. Afterwards, the best technology/-ies to reach the targets of the ramp-up stage can be identified. This must be seen as an extension of the existing approaches, which focus on the evaluation of manufacturing technologies in the stage of series production. Examples for these approaches are the works of Trommer and Müller [11,12].

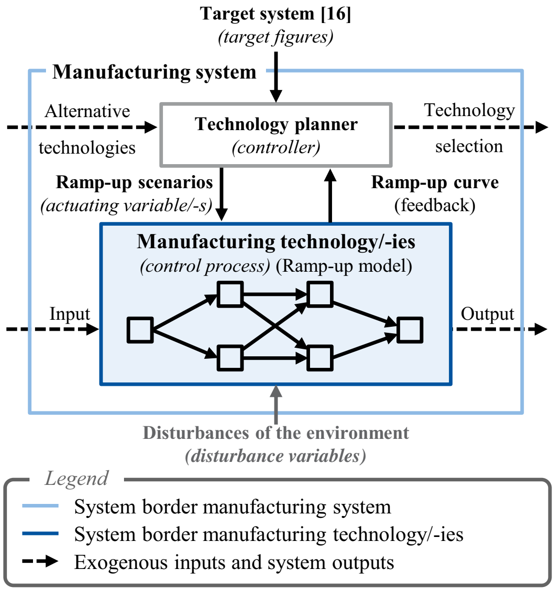

Fig. 2. Ramp-up control loop for manufacturing systems [21]

4.3. System analysis – Determination of composition structure

A simulation based prediction of ramp-up curves of manufacturing technologies requires a modeling of the discrete workpiece flow, which is the next step of the system analysis. This is especially important in case of manufacturing systems consisting of more than one manufacturing technology. The workpiece flow in the ramp-up model follows the general modeling concept according to VDI 3633, see Fig. 3.

The central element in the workpiece flow model of VDI 3633 is a universal processing building block (3), which is represented by one manufacturing technology (C) in the ramp-up model, see Fig. 3. Sources (1) and sinks (5) are the input (A) and output storages (E) of the manufacturing technology in the ramp-up model. Between the manufacturing technology and the storages the provision and the transfer of workpieces must be modeled by buffers (2, 4, B, D), which do not belong to the manufacturing technology and therefore are not modeled in detail. To link two manufacturing technologies, the output storage (E) of the first technology is the corresponding input storage (A) of the second technology.

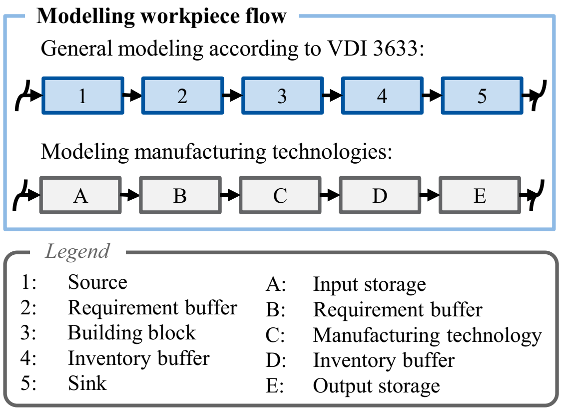

Fig. 3. Composition structure of a manufacturing technology

4.4. System analysis – Analysis of dynamic impacts

The analysis of the dynamic impacts, which cause the dynamic ramp-up behavior of manufacturing technologies (MTs), was divided into two steps. In the first step, the impact categories were determined based on a literature survey. Afterwards, impact factors within these categories were systematically identified. For the systematic identification of the impact factors, the cause-and-effect diagram according to Ishikawa was used [22]. The results of the analysis are summarized in Fig. 4.

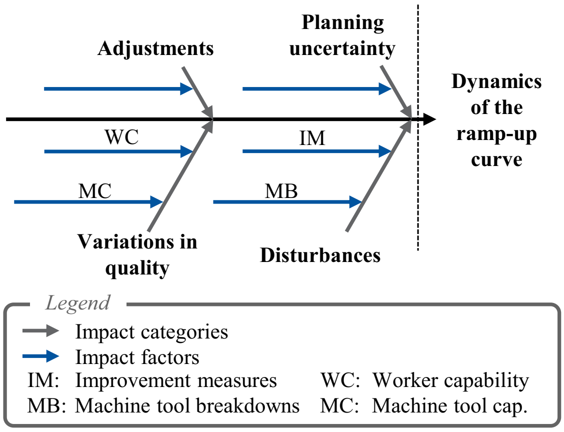

Fig. 4. Impacts on the dynamics of the ramp-up curve of MTs

In the ramp-up stage, the main impact categories of the manufacturing technologies (MTs) are “variations in quality”, “disturbances”, “adjustments”, and “planning uncertainties” [2,8,20,23-27]. For example, in the impact category “variations in quality” the worker capability is modeled by different learning curves depending on the manufacturing technologies deployed and the knowledge of the worker concerning this technology.

According to Renner and Glock, machine tool breakdowns, which are an impact factor in the category “disturbances”, are one of the major reasons for imperfect production during ramp-up [2,23]. Therefore, the impact factor machine tool breakdowns (MB) is described in detail to present the concept of the ramp-up model. The impact $MB_i(j)$ is defined as the present breakdown rate of the machine tool i due to technical disturbances during the manufacturing of workpiece j. The machine tool is divided into different modules m which enables a modeling of the breakdown behavior of machine tools during ramp-up [20]. For every module m of the machine tool i, the dominating breakdown reason during ramp-up has to be determined. The breakdown rate of a module $MB_{i,m}(j)$ can be modeled by two different types of Weibull distributions. For early failures, e.g. software problems of the machine control, the present breakdown rate depends on the time $t_{i,j}$ from the start of the ramp-up until the point in time when the workpiece j is manufactured on the machine tool i, see equation (1). The variable $b_{i,m}$ is the Weibull parameter of the machine tool i and the module m and must be determined by the technology planner. For early failures $b_{i,m}$ must be smaller than one. The variable $T_{i,m}$ is defined as the characteristic lifetime of module m of the machine tool i. In case of failures caused by wear of the module m, e.g. a tool breakage, the breakdown rate depends on the cumulated production time $ct_{h,i,m}$ since the last breakdown of this module, see equation (2). In this case, $b_{i,m}$ must be larger than one. [28]

$$MB_{i,j,m}(t_{i,j}) = b_{i,m} * \frac{{t_{i,j}}^{b_{i,m}-1}}{T^{b_{i,m}}} \qquad (1)$$

$$MB_{i,j,m}(ct_{h,i,m}) = b_{i,m} * \frac{{ct_{h,i,j}}^{b_{i,m}-1}}{T^{b_{i,m}}} \qquad (2)$$

The $MB_i(j)$ has a direct impact on the quality rate $QR_{i,j}$ of the machine tool i, see Fig. 5. The quality rate is defined as the ratio between good parts, which fulfill the quality requirements, and all parts produced [8]. The workpiece j, which is manufactured at the time the MB occurs, is modeled as a scrap part (SP).

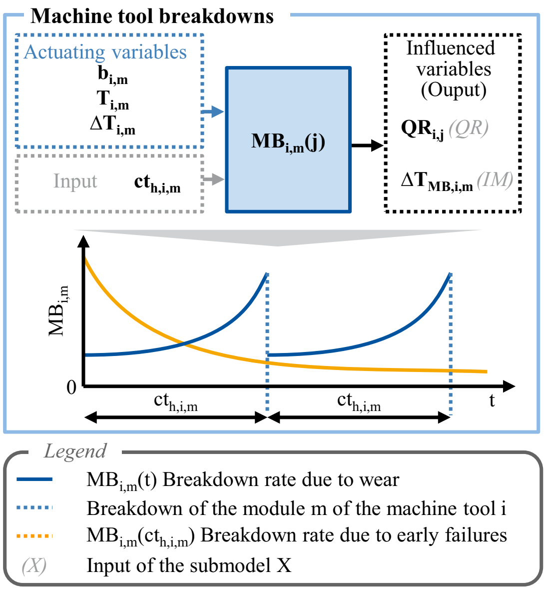

Fig. 5. Modeling machine tool breakdowns (MB)

Furthermore, a MB leads to improvement measures (IMs) conducted at the machine tool i after a MB has taken place, which last for the machine tool breakdown time $\Delta T_{MB,i,m}$. The variable $\Delta T_{i,m}$ is the average time to repair the module m of the machine tool i. This variable is also an input variable of the machine tool breakdowns submodel and is required for the model formalization in chapter 5. An overview of the modeling of machine tool breakdowns is given in Fig. 5. The other dynamic impacts on the ramp-up curve according to Fig. 4 were modeled as well, however will be presented in detail in a further publication due to a limited scope of this paper.

In the second step, the relations between the impact factors and other system variables of the ramp-up model for manufacturing technologies are deduced from the results of the modeling of dynamic impacts in the first step. The relations on the top level are depicted in Fig. 6. As can be seen in Fig. 6, the MBs influence the QR and the improvement measures IMs.

The definition of the logical conditions and decision rules is part of the model formalization in the next chapter. Furthermore, all actuating variables are set by the technology planner, compare Fig. 2. In the next chapter, the developed ramp-up model for manufacturing technologies is formalized and afterwards implemented in Matlab®.

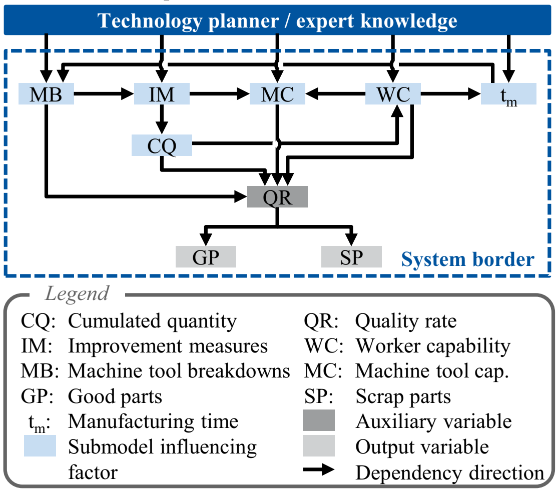

Fig. 6. Relations within the ramp-up model on the top level

5. Model formalization and implementation

In the following, the model formalization is conducted on the example of the availability of the machine tool i. The machine tool i must be available to start the manufacturing process conducted by the machine tool i and depends on machine tool breakdowns MB and improvement measures IM. For the modeling of the availability of the machine tool i a flow chart was developed, which is depicted in Fig. 7.

Firstly, a workpiece j is taken from the input storage to the requirement buffer. Afterwards, it is tested for every module m of the machine tool i whether the machine tool module m is available or a MB has occurred. In case of a MB *[true]* of the module m, the flow stops for the time to repair the module m $\Delta T_{i,m}$ and the workpiece j is modeled as a scrap part. Otherwise *[false]*, it is tested in the next decision block whether an improvement measure is carried out. If not *[false]*, the production process can start (manufacturing). Otherwise *[true]*, the workpiece j has to wait for the time $\Delta T_{IM,i}$ until the improvement measure is completed.

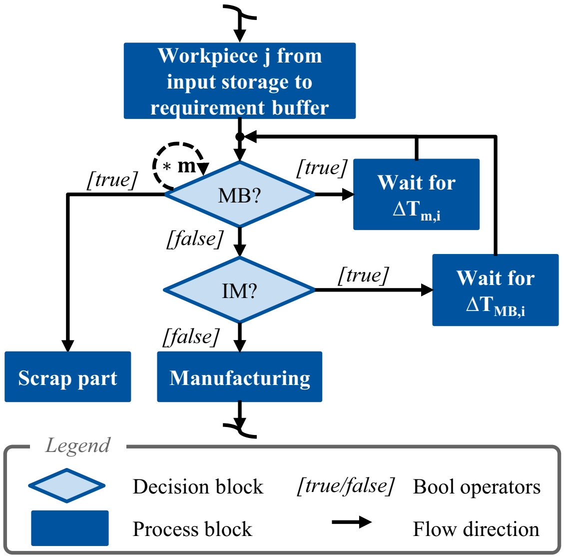

Fig. 7. Flow chart machine tool availability

The last step is the implementation of the formalized ramp-up model into a software prototype. In the present case, the model is implemented in Matlab® Simulink®. Simulink® allows an implementation of complex hybrid simulation models in a hierarchical block structure with a graphical interface. A hybrid simulation approach is needed because the material flow must be modeled by a discrete event simulation. Whereas, the interactions between the dynamic impacts must be modeled with a system dynamics model. The discretization of the dynamic flows is realized by Monte-Carlo-Simulations within the hybrid simulation model and explained in the following. Within the Monte-Carlo-Simulation, equally-distributed pseudo-random numbers between zero and one are generated, compare Fig. 8. By comparing the pseudo-random numbers with the breakdown probability (Weibull distribution) of the module m of the machine tool i, a decision could be made whether a breakdown for workpiece j occurs or not.

6. Model validation

Finally, the developed ramp-up model was validated. The study analyzed the ramp-up performance of two manufacturing systems from a German automotive manufacturer. The actual data is confidential and could not be presented within this publication. For a new engine generation it was considered, whether it is possible to integrate a new more productive and less expensive manufacturing technology for the coating process of the cylinder running surface without missing the ramp-up target "time-to-market" of 200 good parts per shift after 2000 h.

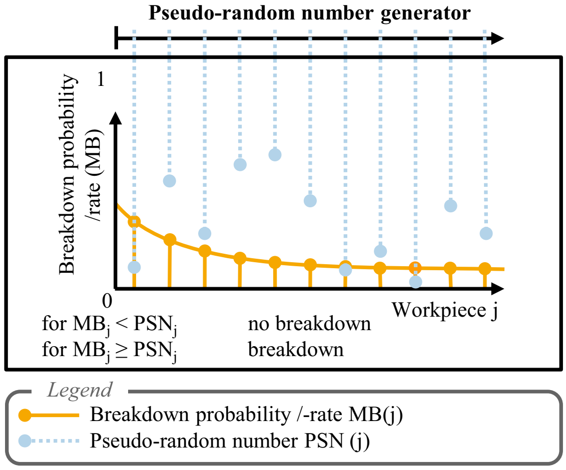

Fig. 8. Discretization with Monte-Carlo-Simulation

Therefore, the ramp-up curves of the old (galvanic coating) and the new manufacturing technology (High-Velocity-Oxygen-Fuel (HVOF)) were calculated with the developed ramp-up simulation model and the results were evaluated. The galvanic coating technology was an established process in the company and had been applied for the previous engine generation in the company. Therefore, the capability of the machine tool MC and the workers capability WC were estimated by technology experts as high. Whereas, the learning rates of the worker and the impacts of improvement measures were set as low. For the new technology, which was not established in the company, the machine tool and workers capability were low compared to the old technology. Additionally, there was a large improvement potential of the new technology due to learning of the workers and improvement measures of the machine tool. Furthermore, machine tool breakdowns were much more likely for the new technology than for the old one. After setting all initial values of the simulation model by the technology planner, the simulation was executed in Matlab®. The simulation results are shown in Fig. 9 and are discussed in the following.

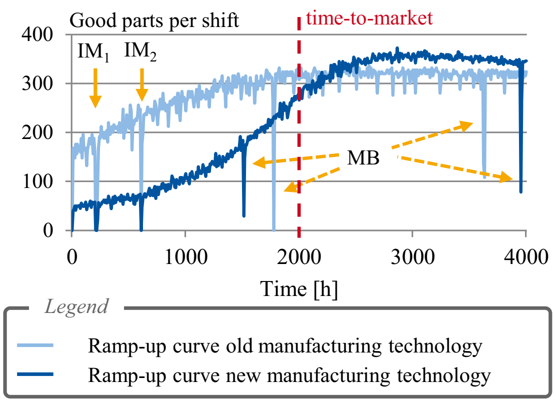

Fig. 9. Simulation results of the case study

The results of the simulation showed, that at the beginning the new manufacturing technology produced significantly less good parts than the old one which was in good accordance with the observations of the real manufacturing systems. Furthermore, the ramp-up curve of the new technology was steeper due to learning effects, which led to a higher workers capability and improvement measures influencing the machine tool capability. Both manufacturing technologies were able to meet the target "time-to-market" of 200 good parts per shift after 2000 h. Due to the higher productivity and the lower manufacturing costs of the new technology, this technology has been implemented for the manufacturing of the new engine generation. In addition, the new technology could produce more good parts than the old one after around 2200 hours. This was in accordance with the technological specification of the HVOF, which had a lower cycle time than the galvanic coating process.

7. Summary and Outlook

This research paper presents a basic model for the prediction of ramp-up curves of manufacturing technologies. Firstly, the research procedure for the model development is explained. Secondly, the generic ramp-up model based on a control loop and the production theory according to Dyckhoff is introduced. In the following, the model development is presented in detail with a focus on machine tool breakdowns. Finally, the model is applied for a case study from the automotive industry for two different manufacturing technologies. The results show that the ramp-up model is able to consider the characteristics of different manufacturing technologies and calculate their ramp-up curves, which can serve as a decision support for the technology planner. In another publication the ramp-up model and further submodels of the dynamic impacts will be presented in detail. Furthermore, case studies of manufacturing systems with several technologies and an optimization of the present ramp-up model, e.g. regarding the simulation time as well as the model calibration for different manufacturing technologies, will be also addressed in future work.

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